

Seismology of Accreting White Dwarfs

Phil Arras¹, Dean Townsley², Lars Bildsten^{1,2}

¹*Kavli Institute for Theoretical Physics, Kohn Hall, University of California, Santa Barbara, CA 93106*

²*Department of Physics, Broida Hall, University of California, Santa Barbara, CA 93106*

Abstract. Pulsation modes have recently been observed in a handful of white dwarf (WD) primaries of cataclysmic variables, allowing an interesting new probe into the structure of accreting WD's. We briefly discuss the seismology of these objects, how stellar properties may be inferred from the observed mode frequencies, and mode driving mechanisms. For one pulsator, GW Lib, we have shown that a WD mass $M = 1.05 M_{\odot}$ and accreted envelope mass $M_{\text{env}} = 0.4 \times 10^{-4} M_{\odot}$ give the best match to the observed pulsation periods. A first exploration of mode driving favors $T_{\text{eff}} = 14000K$ and a massive WD, but more work is necessary.

1. Introduction

Pulsation modes have been observed in isolated white dwarfs for several decades. Since the observed mode periods are sensitive to the WD structure, an industry has emerged to estimate parameters such as WD mass, light element envelope mass, and rotation rate from observed the mode periods (for a review, see e.g. Bradley 1998). GW Lib is the first discovered accreting, pulsating white dwarf (van Zyl et al. 2000). It is the shortest orbital period cataclysmic variable (CV) known at $P_{\text{orb}} = 77$ min (Thorstensen et al. 2002), and is observed to have dwarf nova outbursts. In the last few years, a handful of additional accreting pulsators have been found in dwarf nova systems (see table 1.) and roughly a dozen more are expected, raising the possibility of using seismology to determine parameters for a number of accreting WD in CV's.

Mass determinations for WD in CV's are especially interesting due to possible implications for progenitor systems of Type Ia supernovae. Thought to be accreting WDs near the Chandrasekhar mass (Hillebrandt and Niemeyer 2000), these progenitors are closely related to the CV population, but the precise nature of this relationship is unknown. Important clues in this mystery lie in how the masses of CV primary WDs change over the accreting lifetime of the binary, but progress is hampered by the difficulty of measuring CV primary masses (Patterson 1998). This mass evolution, as well as measuring the accreted mass directly with seismology, is also important for determining how much, if any, of the original WD material has been ejected into the ISM in classical nova outbursts, contributing to the ISM metallicity (Gehrz et al. 1998).

In this proceedings, we first review how seismology can be used to infer stellar parameters. Next we discuss possible mechanisms for how modes might

Table 1. Known Accreting Pulsating White Dwarfs

System	Mode Periods [sec]	References
GW Lib	236, 377, 646	Van Zyl et.al. (2000,2004)
SDSS 1610	345, 607	Warner and Woudt (2004)
SDSS 0131	330, 600	" "
SDSS 2205	330, 600	" "
SDSS 1556	834, 1137, 1558	Warner and Woudt poster, this meeting
SDSS 1556	834, 1137, 1558	" "
HS 2331	60, 300	Araujo-Betancour et.al (2004)

be driven in accreting WD. We outline the differences between seismology for the accretors and isolated WD.

2. Structure and Seismology of Accreting White Dwarfs

In this section we first contrast the structure of accreting versus isolated WD, and then discuss how these differences in structure affect the mode periods.

Isolated WD are observed to pulsate in narrow ranges of temperature: $T_{\text{eff}} \sim (11 - 12) \times 10^3 \text{K}$ for hydrogen (DAV) envelopes (Bergeron et al. 1995) and $T_{\text{eff}} \sim (21 - 24) \times 10^3 \text{K}$ for helium (DBV). Sedimentation times near the WD surface are sufficiently short that the composition is essentially pure H or He for these relatively old WD. Isolated WD are passively cooling, with the flux being generated by the hot C/O core. The size of the surface layer of light elements (H or He) is determined by late stages of nuclear burning and winds, and is rather poorly constrained by stellar evolution theory (D’Antona & Mazzitelli 1990).

Envelopes in WD accreting from a companion inherit the companion’s composition. The envelope thickness builds to the ignition mass $\sim 10^{-4} M_{\odot}$ at which point a thermonuclear runaway occurs, ejecting some fraction of the envelope, and the process starts over. Accretion at a time-averaged rate $\langle \dot{M} \rangle$ generates a “compressional heating” luminosity (Townsley and Bildsten 2004) $L \sim \langle \dot{M} \rangle k_B T_{\text{core}} / m_p$ at the base of the envelope, and determines the equilibrium core temperature over long ($\sim \text{Gyr}$) timescales. The temperature profile differs from an isolated WD since the flux is generated at the base of the envelope, not uniformly in the core.

Gravity waves (g-modes) are restored by buoyancy in stably stratified regions. The dispersion relation for short wavelength g-modes is $\omega = N k_h / k_r$, where N is the Brunt-Vaisalla (buoyancy) frequency, $k_h^2 = l(l+1)/r^2$ is the angular wavenumber for a mode with angular dependence Y_{lm} , and k_r is the vertical wavenumber. Waves propagate where the vertical wavelength is shorter than the characteristic lengthscale associated with the background. Hence waves are reflected from the center and surface, and composition discontinuities act to create separate resonant cavities, at least for long wavelength modes. For massive and/or cold WD with solid cores, g-modes cannot penetrate the core. The propagation diagram for a model of GW Lib with WD mass $M = 1.05 M_{\odot}$ and

envelope mass $M_{\text{env}} = 0.3M_{\text{ign}} = 0.40 \times 10^{-4}M_{\odot}$ is shown in the upper panel of Figure 1. The large peak in N at $\log_{10} p \simeq 19$ is due to the change in mean molecular weight in the transition layer from the solar composition accreted envelope to the C/O core. In the roughly constant flux envelope, $N^2 \simeq g/z$ where z is the depth into the star from the surface. In the degenerate core, $N^2 \simeq (g/H_p)(k_b T/E_F)$ drops rapidly toward the center, where E_F is the electron Fermi energy and $H_p = p/\rho g$ is the pressure scale height.

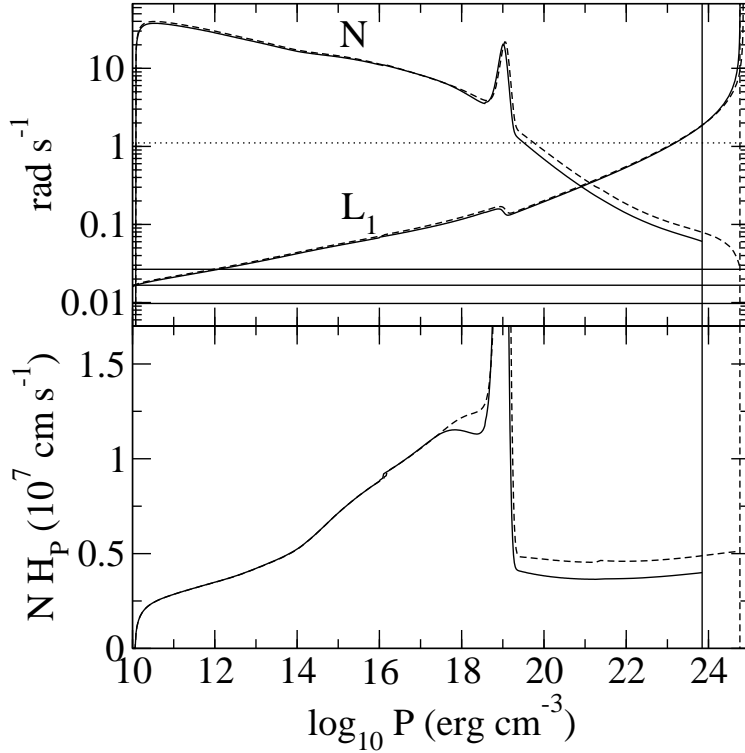


Figure 1. Comparison of propagation diagram (top panel) and WKB integrand (bottom panel) for an accreting model (solid lines) and non-accreting model (dashed line) with the same composition and T_{eff} . The vertical solid (dashed) line on the right indicates the liquid-solid boundary. The solid horizontal lines are the three observed frequencies for GW Lib and the dotted horizontal line is the breakup frequency. The accreting model has $M = 1.05M_{\odot}$, $M_{\text{env}} = 0.3M_{\text{ign}} = 0.40 \times 10^{-4}M_{\odot}$, $T_{\text{eff}} = 16070$ K (that implied for this M by the UV spectrum), $\langle \dot{M} \rangle = 6.4 \times 10^{-11}M_{\odot} \text{ yr}^{-1}$, and $T_{\text{core}} = 5.9 \times 10^6$ K. The non-accretor has $T_{\text{core}} = 9.3 \times 10^6$ K.

The contribution to the eigenfrequency from a particular part of the star can be estimated from the WKB phase integral $\int dr k_r = [l(l+1)]^{1/2} \omega^{-1} \int dr N(r)/r \approx n\pi$, hence $\omega \propto \int dr N(r)/r \propto \int d \ln p H_p N$, where we have taken the radius to be approximately constant in the last expression. The integrand is shown in the bottom panel of Figure 1, representing the number of nodes per decade in pressure. Shown are two WD models: an accreting model with $M = 1.05M_{\odot}$ and $M_{\text{env}} = 0.3M_{\text{ign}} = 0.40 \times 10^{-4}M_{\odot}$ used in our mode analysis (solid line),

and a non-accreting model with the same T_{eff} (dashed line) and composition. Not shown in Figure 1, but perhaps the largest effect, is the difference due to the envelope mean molecular weight, μ , from the case of a pure H or He envelope to one of solar composition. Such a change is reflected in the periods as $P_n \propto \mu^{0.5}$, since the envelope is well-approximated by an $n = 4$ polytrope. The non-accreting model also has a higher T_{core} than the accreting model by about 50%, leading to two important effects: (1) the WKB integrand has a higher value in the core for the non-accreting model ($\omega \propto T_{\text{core}}^{1/2}$), and (2) the solid core is smaller, pushing the inner boundary condition deeper into the star. Both effects directly influence the observed periods, and period spacings, hence *it is essential to use a WD model including the effects of compressional heating and nuclear burning*, rather than a passively cooling WD model.

To get an analytic idea for how stellar parameters can be estimated from mode frequencies, consider first the nondegenerate envelope. In this region, $N^2 \sim g/z$ giving a frequency $\omega \sim [l(l+1)]^{1/2} n^{-1} (g/H)^{1/2} (H/R)$ for a mode with quantum numbers l and n trapped in an envelope with base scale height H and stellar radius R . For a mode trapped in the degenerate core, $\omega \sim [l(l+1)]^{1/2} n^{-1} (g/H)^{1/2} (k_B T_{\text{core}}/E_F)^{1/2}$. Given observed mode periods, and assumptions about the l quantum number, one can attempt to identify the n quantum number of the modes, and infer stellar parameters such as mass and envelope mass using these expressions.

Townsley, Arras, and Bildsten (2004) have used the model of accreting WD thermal structure from Townsley and Bildsten (2004) in the first study of seismology of accreting WD. They computed oscillation mode periods using an adiabatic code, and identified the WD model most consistent with the three observed mode periods (assumed to be dipole) for GW Lib, the best observed accreting pulsating WD. The best fit was a WD mass $M = 1.05 M_{\odot}$ and accreted envelope mass $M_{\text{env}} = 0.3 M_{\text{ign}} = 0.40 \times 10^{-4} M_{\odot}$. Such a large inferred WD mass has consequences for mode excitation, discussed in the next section.

3. Excitation of G-Modes in Accreting White Dwarfs

We are motivated to understand how mode excitation might be different in accreting WD for two reasons. First, Szkody et.al. (2003) have determined an effective temperature for GW Lib of $T_{\text{eff}} = (14 - 17) \times 10^3$ K, depending on how the fit was done. These estimates are well above the standard DAV instability strip $T_{\text{eff}} \approx (11 - 12) \times 10^3$ K, implying that convective driving, and also the κ -mechanism, cannot drive the pulsations for a fiducial $M = 0.6 M_{\odot}$ pure hydrogen envelope. Secondly, the WD mass may have increased after Gyr's of accretion, motivating study of WD heavier than the canonical $M = 0.6 M_{\odot}$.

A large literature exists on excitation of g-modes in isolated WD. Initially investigators expected the “ κ -mechanism”, associated with opacity variations in an ionization zone, was the driving mechanism (Dziembowski and Koester 1981). Later, with penetrating insight, Brickhill realized that the response of surface convection zones to a g-mode pulsation naturally acts to pump more energy into the mode, hence the name “convective driving” (Brickhill 1983; Brickhill 1991). Wu and Goldreich have confirmed Brickhill's result, and extended its consequences, notably in the area of nonlinear saturation mechanisms (see the series

of papers starting with Goldreich and Wu 1999). The criterion for a mode to be unstable is roughly $\omega\tau_{\text{th}} \geq 1$, where $\omega = 2\pi/P$ is the mode frequency, P is the period, and τ_{th} is the thermal time at the base of the ionization zone, which coincides with the base of the convection zone. The “blue edge” of the instability strip in effective temperature occurs when the shortest period g-mode is unstable by this criterion; g-modes should be observed for temperatures below the blue edge. For DAV and DBV’s, observationally there is a “red edge” below which pulsations are not observed. The reason for this cutoff is not as well understood, but may have to do with the luminosity perturbation becoming small, even if the mode amplitude is large (Brickhill 1983).

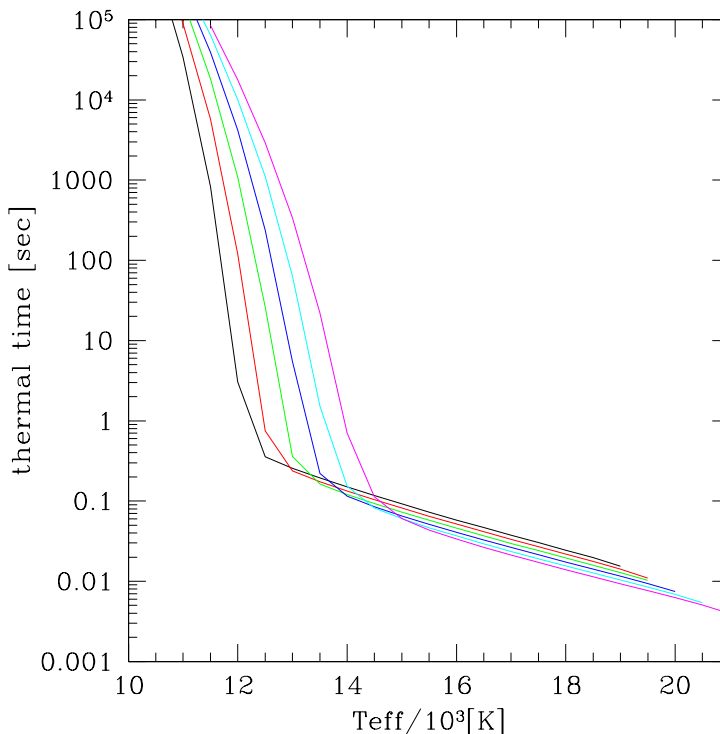


Figure 2. Thermal time at base of convection zone vs. T_{eff} for different gravity, but fixed (solar) composition $X = 0.7$ and $Z = 0.02$. The gravity in cgs units for each line is, from left to right, $g = 10^{8.0}$ (black), $10^{8.2}$ (red), $10^{8.4}$ (green), $10^{8.6}$ (blue), $10^{8.8}$ (cyan), $10^{9.0}$ (magenta).

What is the instability strip for accreting WD? Here we investigate the thermal time at the base of the convection zones as a function of gravity (fig.2). We use the OPAL opacity and equation of state (Iglesias & Rogers 1996) to construct solar composition, plane parallel, constant gravity and flux envelopes, using standard mixing length (Kippenhahn and Weigert 1990) in convective regions. In fig.2, gravity is varied from $g = 10^8 \text{ cm s}^{-2}$ ($M \approx 0.6M_{\odot}$) to $g = 10^9 \text{ cm s}^{-2}$ ($M \approx 1.2M_{\odot}$). We define a fiducial blue edge to be at $t_{\text{th}} = 100$ sec.

This blue edge moves to the right by ~ 2000 K over a factor of 10 change in gravity.

We confirm the suggestion by Szkody et.al. (2003) that GW Lib may pulsate because it is a massive WD. If GW Lib has a high surface gravity such that the blue edge moves up to $T_{\text{eff}} \approx 14000\text{K}$, it may overlap with the lower value stated for the observed T_{eff} . A large WD mass $M \approx 1.1M_{\odot}$ was also preferred in the parameter estimation of Townsley et.al. (2004) using seismology.

Additional factors not discussed here may influence seismology and g-mode driving in accreting WD. The structure of composition transition layers is different for accretors due to the downward accretion flow, and the composition of layers overlying the core is uncertain due to classical novae. Hydrogen depleted donor stars are expected for binaries with orbital periods $\lesssim 1$ hr, increasing the blue edge somewhere in between that of DAV's and DBV's. Metals may act as an additional *damping* mechanism (cool WD are on the wrong side of the "metal bump"). Sedimentation in between dwarf novae outbursts may occur in the accreted near solar composition layer, even down to the driving region at $p \sim 10^{10} \text{ erg cm}^{-3}$, creating helium "puddles" sandwiched in between hydrogen and solar composition layers. Seismology for WD spun up even to modest rotation rates will be quite different than the nonrotating case, changing the expected mode periods qualitatively. Finally, new instability strips may occur outside the traditional DAV and DBV regions due to changes in mode properties arising from rapid rotation.

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